Rob Meyer - Rob Meyer Productions

1031 N. Deer Glen Pl.
Tucson, AZ 85745
(520) 623-6126
rmeyer@robmeyerproductions.com

Technical Paper for DARPA Grand Challenge
Rob Meyer Productions / Coyote Autonomous Vehicle System

1. System Description

A. Mobility

1. - Ground Contact: The Coyote Vehicle is a four-wheeled, rear-wheel drive buggy. It has a four-link rear suspension, a double A-Arm front suspension, coil-over hydraulic shock absorbers in the front, and a combination of torsion bar springs and coil-over hydraulic shock absorbers in the rear.

2- Locomotion: The vehicle is powered by a four-cylinder automotive internal combustion engine *(Toyota 22R)* driving an automatic transmission (hydraulically shifted planetary gears), to a Hotchkiss style rear axle/differential assembly. Further gear reduction at the wheels (2:1 hub mounted *1 ½" Ramsey RPV* chain drives) provides the torque and additional ground clearance necessary to drive the *58" tall tires*. Steering is provided to the front wheels by an automotive style power *worm/recirculating ball* set. Brakes are 2-circuit hydraulic disc with *two discs at the front wheel hubs. There are no brakes on the rear wheels. The change in the braking configuration was made after evaluation of vehicle front to rear weight bias, rear unsprung weight, and tire contact patch. By putting the brakes at the front of the vehicle, we shed unsprung weight from what turned out to be a very heavy rear wheel drive axle, we put all of the braking impulse at the front of the vehicle toward the direction of weight transfer, and we shorten and consolidate brake lines, sensors and other components into the front half of the vehicle. In locating the brakes to the front of the vehicle, we upgraded them to 12" ventilated discs.* Note that the system is still a balanced two-circuit system with separate left and right circuits. A single leak would not result in total brake failure. As will be described later, the resultant effect of partial brake failure on the steering would be compensated for by a closed circuit feedback control system to the steering gearmotor, which would attempt to counter steer in such an event. In addition, we have kept the odometer on the axle with no brakes. This allows us to sense a skid or inadequate braking impulse. We have no algorithm for the former. For the latter an activation of the pneumatic emergency-braking cylinder would result, followed 3 seconds later by termination of power to the engine ignition.

3- The throttle of the engine is actuated by a PWM style servomotor attached directly to the throttle body. Gear selection is through a permanent-magnet gearmotor mechanically linked to the shift mechanism and controlled by an *h-bridge relay arrangement with microswitch position feedback.* The hydraulic assist steering is actuated by a permanent-magnetgearmotor linked to the steering shaft and controlled by a PWM motor controller with a *rotary potentiometer* feeding steering movement back to the steering microcontroller. Primary Brakes are actuated by a permanent magnet DC gearmotor driving a two-circuit hydraulic brake master cylinder. Overall braking impulse is fed back to the braking microcontroller by a *pair of adjustable hydraulic pressure switches, one set for braking to slow (about 800 psi) and the second set for braking to hard stop (about 1000 psi.)* In addition, a secondary braking system is being built that will impart a charge of pressurized CO2 gas to a pneumatic cylinder tied in tandem to the master cylinder in a mutually exclusive linkage, allowing either system to operate should the other be jammed or otherwise inoperative. The secondary braking system will come into play through a software controlled panic stop or an external e-stop command. It is being included for safety both as a backup to the primary brakes and because it has a much faster response time than the gearmotor driven system.

B. Power

1. Power comes from the 120 horsepower I.C. engine. The engine alternator maintains a charge on one 12-volt 850 Ah automotive sealed lead-acid battery for starting, chassis electrical, *and navigation and sensing systems.*

2. The I.C. engine and its associated electrical components could consume up to 90 Kilowatts, though the average consumption would be much less.

3. The vehicle will carry *22 gallons* of DOT 89-90 Octane Gasoline Motor Fuel.

C. Processing

1. The computing hardware onboard consists of one *Toshiba Satellite 2535 CDS Pentium laptop* CPU running a BASIC navigation and control program on Microsoft DOS. The CPU's function is to receive position and environment data from the other systems on board, to analyze the data, make route finding decisions, and to output control signals to the vehicle. A total of seven peripheral microcontrollers are networked to the serial communications port of the CPU via RS-232 link. All seven microcontrollers are Parallax Basic Stamp II series microcontrollers. The functions of the seven peripheral microcontrollers are: basic processing and transmission of images from the Omnivision CMOS image sensor, processing and interpretation of the two laser rangefinder/terrain mappers, integration of the odometer and solid state magnetic compass, engine and transmission status and control, steering and brake status and control, interpretation of GPS data, *and operation of the three sonar range finders.*

2. Most interpretation of sensor data will happen within the CPU and its associated program, although some minor tasks will be handled by the peripherals. The hierarchy of decisions for navigation and route finding will start with the RDDF. To simplify the

enormous computational task the vehicle is faced with, we wrote our software to tackle the route one leg at a time. For the purposes of this description we will set aside timekeeping, vehicle status monitoring and other housekeeping tasks the program would of course need to monitor as it made its way. Navigation starts with the first two RDDF waypoints, lateral boundary width (which we call track width), and speed limit being read from the file. The purpose of this arrangement is that it allows us to leave the center of track to avoid obstacles, make course corrections, etc, without the vehicle straying too far off course. For each time the vehicle leaves the center of track, it computes the distance it has traveled. This process continues ad infinitum until each intermediate waypoint is passed in succession. When the vehicle senses the entire leg is finished, it reads the next set of RDDF data and continues on. We originally had the vehicle completing a hard 180-degree turn to reverse its course, but it was decided the reversing 3-point turnabout would take less space and allow the vehicle to pass back over terrain it had already cleared for the most part.

Objects are classified according to their height, distance from the vehicle, and the speed of the vehicle when the object is detected. The *long-range laser ranger*, scanning laser rangefinder, and sonar will only detect objects as range data returns or "echoes". The long-range laser device will detect only large objects, vehicles, and terrain features at long range; the scanning laser rangefinder will detect objects. The sonar will detect objects of any size from a fraction of an inch wide and up, but at a range of less than 50 feet. The video camera has an algorithm that samples the mean color data from a center window in the camera's view, and then tries to identify the widest area in view that matches that color. This is an aid to decision making for the main program designed to help differentiate between ground clutter and what could be a clear road or trail. It is not hard data to be responded to, but it is a factor that the main routine uses to weight its decision when course changes are necessary. We decided to do away with the long-range radar after we found it to be hard to focus and unreliable in the returns it provided. We opted instead for a fixed long-range laser rangefinder which is much more reliable, and precise. It is set at a fixed angle to read optimally 500 feet ahead and provide early warning of large objects or changes in elevation only when the vehicle is operating near top speed and needs to be slowed.

Our selection of sensing instruments is such that the combination of sensors and their range will allow them to reliably detect objects 18" high by 6" wide and larger in time for the vehicle to avoid the object at a given speed. The vehicle is designed so that it will be able to roll over most objects smaller than this either by straddling the object entirely, or by rolling over it with its tires. We determined that it was necessary for the vehicle to tolerate this since designing the sensors to differentiate between a field of 18" tall sage plants and a field of 18" boulders is difficult to accomplish with any reliability at road speeds. It should be noted that when such conditions are present, the vehicle would be held to its projected average ground speed. The vehicle will only accelerate past this speed when it receives no obstacle data and a clear path image (assuming these clear returns are valid data from active sensors).

For normal course corrections that do not involve avoiding obstacles, the CPU simply transmits the required steering command to the appropriate peripheral where the command is translated into pulse width modulated motor control signals. All control commands are integrated with vehicle status information to ensure safe operation. For instance, steering angle is limited by vehicle speed. If the vehicle is attempting to avoid an obstacle, it first decreases throttle opening, then it brakes, and then it applies steering input. As the vehicle speed slows the amount of steering input is increased proportionally to allow the vehicle to produce the maximum safe steering response for a given speed. This allows for the quickest, safest evasive actions possible. The actual "curve" of vehicle speed versus steering input limits is in the process of being determined experimentally.

D. Internal Databases

1. At this time we do not anticipate having any internal databases onboard other than the RDDF. At the scale we will be operating, we do not anticipate any available mapping or terrain data will be of much use. Terrain and mapping data will be acquired "on the fly" by onboard sensors as the vehicle progresses. We are, however, looking into hard-coding flags into the navigation routine that would indicate on which legs of the course improved roads might be present according to published mapping data. With the flags inserted into the program, the existing algorithm would have one more bit of data to weight its decisions. It could then instruct the camera along those legs of the course to look for mean color data that approximate pre-sampled records of both paved and dirt roads along the course.

E. Environment Sensing

1. Object detection and classification will happen in layers according to vehicle speed. At the farthest range, our *laser range finder* detects and returns ranges of large objects and terrain features up to 500 feet away. *This instrument is a standard industrial laser rangefinder, set to return ranges at the ground level 500 feet ahead 3 times per second*. This return will not necessarily result in a control command to the vehicle; it is used instead as a decision-making tool for avoiding obstacles that approach more closely to the vehicle.

The closest practical range at which objects will be detected is between 100 and 200 feet, when the scanning laser rangefinder will begin returning ranges. The laser instrument is mounted at 90 inches from ground level, and is aimed at ground level 200 feet ahead of the vehicle. The instrument is a scanning time-of-flight device. The above mounting arrangement is necessary in order to keep the CPU from interpreting bounce induced changes in angle of the instrument as being actual changes in terrain.

At the lower end of the sensing range is the sonar set. The sonar consists of *three* fixed Polaroid 6500 series sonar ranging modules that operate in the 50-foot range. They are meant for obstacle avoidance in low-speed close quarters maneuvering, or as the last sensing step in a series of longer-range returns from other sensors. Nonetheless, the range of the sonar will make it useful for direct obstacle avoidance only in the sub 10 mile per hour speed range. With one module "looking" to each front quarter of the vehicle, and *one "looking" straight ahead*, passing between closely spaced objects or through confined spaces is possible.

As mentioned, an Omnivision digital image sensor array will also be employed for path identification. Although the vehicle would never rely solely on input from this camera for navigation, it will use the information in an attempt to identify the center of clear paths or roads that might coincide with the route. In our experiments in the field, we tried to identify some commonality between dirt roads, paths, and paved roadways. What we learned is that visually all that they have in common is that they often consist of some uniform color and or texture in contrast to their surroundings. We are programming our vision microcontroller to wait for clear path situations as identified by the other vehicle sensors, then to sample a centroid window of an image of that path. The camera then attempts to track the mean color data of that sample along a path and to send steering inputs to the CPU in an attempt to bring the vehicle to the center of the path. If no path exists, or the camera otherwise does not identify one, it waits for the next clear path situation to try again. If the camera did identify a path and successfully centered the vehicle on it, it would continue to steer the vehicle down that path as long as it did not disagree with the computed route or any obstacle data. As it does so the camera will update itself with a fresh centroid image of the path once every few seconds to adjust for changing lighting conditions, road texture, etc.

Finally, a Thales A12 GPS receiver, *in tandem with a CSI Wireless differential beacon receiver,* is mounted to the instrument deck toward the front of the vehicle. GPS data will be handled through the GPS microcontroller where RS-232 query commands from the CPU will be translated and sent to the receiver and position data will be buffered, filtered, and sent back to the CPU.

2. The scanning laser rangefinder, digital camera, and *long-range laser* are mounted atop the vehicle on a platform. This is on top of a wheeled vehicle. The highest point is approximately 90" total above ground in height, or about 24" above the top deck of the vehicle. The sonar sets are mounted along the lower front edge of the vehicle body.

F. State Sensing

1. The vehicle will employ just a few sensors for sensing state. It will derive pitch and roll relative to ground from the scanning laser rangefinder. *Ground speed is now derived from an optical interrupter linked to the transmission output shaft*. This was opted for over the magnetic wheel odometers when it was realized the wheel magnets would be vulnerable to damage. Also, placing the odometer at the rear axle allows for accurate speed sensing and effectiveness of braking at the front wheels. The CPU, to periodically compute a correction factor for the odometers, will use the GPS ground speed return. This will allow the vehicle to compensate for slight changes in tire diameter due to wear, altitude/pressure change, etc. In this way, should the odometer be needed during momentary losses of GPS signal, they will be as accurate as possible. Otherwise, speed over ground will primarily come from the GPS receiver. A solid-state magnetic compass module will be used in conjunction with the odometer to dead-reckon the course should there be a loss of GPS signal. Like the odometers, the GPS will attempt to recalibrate the compass at intervals to account for magnetic geoid variations, local EM noise, etc. A tachometer consisting of an induction sensor/counter on the IC engine ignition system provides engine speed data to the engine/transmission microcontroller. This in turn provides feedback to the CPU for gear range selection and to aid in initial engine starting, detecting engine stalls, and engine restarts. There are no other "typical" engine status

sensors on the vehicle, as they would have little use. In a real-world application this would not be the case, but within the limits of this event it is advantageous to keep things as simple as possible.

2. The engine/transmission microcontroller will monitor the engine speed and compare it continually with odometer speed returns and throttle commands relayed from the CPU. It will then make decisions of gear selection and throttle position based on those data. The only useful control feedback the engine/transmission micro will send back to the CPU is when the vehicle speed is too low for the given throttle opening and gear position, as when the vehicle has struck an immovable object or is attempting to climb a very steep grade. In such case the CPU interprets this data and first attempts to steer toward a lower grade. If vehicle speed does not increase after a few seconds, if there is no detectable lower grade, or if the vehicle has stopped, the CPU directs the vehicle to reverse to a distance equal to twice its turning radius and then to select an alternate course as if it were avoiding an obstacle. If such a situation results in an engine stall, the CPU branches to an engine/vehicle restart subroutine.

G. Localization

1. Much of the localization process has been mentioned elsewhere in this paper. To clarify, Differential GPS is our primary means of determining location. The CPU continuously compares the GPS Lat/Long return to a theoretical mathematical representation of position that the main program arrives at through applying trigonometric functions to the RDDF data. This program attempts to keep the vehicle in the center of track, straying only long enough to avoid obstacles. The GPS data is used to keep the two main non-GPS instruments-the odometer and the magnetic compass-continuously calibrated.

2. In the case of GPS outages, the CPU saves its last known location, then begins monitoring distance versus heading data from the odometers and compass in an attempt to stay close enough to center of track by dead-reckoning to avoid going out of bounds. These data are actually monitored at all times anyway; they only come into play when the GPS micro sends a signal to the CPU advising loss or degradation of signal. The vehicle speed will slow to the "target average speed" during GPS outages in order to increase lead-time on obstacle avoidance and other processing tasks associated with dead reckoning.

3. The challenge route boundaries will usually not be detected directly, but rather by the main program's counting off of the distance and angle the vehicle has traveled from track center. This approximation of the boundary location, given generous leeway by the software, should suffice to keep the vehicle on course the majority of the time. In instances of close quarters, narrow track widths, and/or GPS outages, though, the sonar and video will still be employed to avoid any perceived obstacles. So if the boundary is marked in someway in tight areas, the vehicle will sense it as an obstacle regardless of whether or not it still has the ability to determine its location at the time.

H. Communications

1. No information will be broadcast from the vehicle during the event.

2. The vehicle will receive L1 and SBAS GPS signals, and *RTCM correction data from the DGPS radio beacon receiver.* We regret that time did not allow us to pursue another idea past a few initial experiments.

I. Autonomous Servicing

1. The vehicle will need no servicing during the race.

J. The vehicle will be controlled for "taxiing" into position, loading and offloading from trailers, etc. by PPS FM Digital radio control. The receiver will control the vehicle by sending commands directly to the CPU, the main program of which will poll for the presence of an input from the radio control's fail-safe device. Any detection of such a signal would interrupt the main routine and turn all control, (except for the E-Stop routine), over to the radio. The radio receiver will be physically removed from the vehicle prior to the event.

2. System Performance

A. Previous Tests

1. To date we have tested the GPS receiver, DGPS beacon receiver and their associated microcontroller interface, and found it to be within 1 meter of accuracy along the latitude axis, but at around 3 meters longitudinally. We have not been able to get any better accuracy here in southern Arizona, but we are curious to see how it works in the location of the course. We have tested the sonar set and found it to be reliable and functional for detecting objects at the 50-foot range. The video camera works, and we have been testing and running routines through its micro regularly. Initial tests of the path-tracking program were promising, but it was sporadic in differentiating roadbeds from the surrounding area. Although we have not been able to improve on it much since our last writing, we have found that it is a useful and functional aid in finding the center of the road when one exists. As we mentioned earlier, after numerous tests and attempts to calibrate the radar for our application, we opted for a more reliable laser rangefinder to take its place. The navigation and route finding program itself appears to work. Based on the earlier simulation we had written, we are still busy at this date (24 Feb) arriving at an optimum arrangement and timing for the peripherals to "talk" to each other. We will be spending the upcoming two weeks before the event field testing the system thoroughly, and verifying that the E-Stop and Tracking radios work without interference from either system.

B. Planned Tests

Over the next two weeks we will be continuing to take the vehicle to those limited locations where we can test it locally. Unfortunately we had a tougher time getting permission to run the vehicle on state trust lands than we had expected. We also still have to do some extensive testing with the scanning laser, but we now must familiarize ourselves with its operation on our vehicle. Finally, we intend, as mentioned above, to do extensive trials with the E-Stop at each outing.

3. Safety and Environmental Impact

A. The top speed of the vehicle will comply with the given standards.

B. The maximum range of the vehicle with its current fuel cell is about 350 miles.

C. Safety Equipment

1. The fuel cell is a racing style open-cell foam baffled plastic tank with a safety rollover valve and vent check valve.
2. At this time, we do not anticipate including any fire suppression equipment. If the rules dictate that we do so, we will install it.
3. An audible horn in compliance with the rules has been installed. A single amber rotating beacon will be mounted at the top of the sensor dome.
4. A set of two (2) DOT red lens brake lights have been added to the rear of the vehicle in compliance with the latest rules updates. The lights show red from the rear and amber from the front so that vehicle braking can be monitored from any direction.
5. In addition to the External E-Stop manual pushbutton, an external Master Battery Disconnect Switch is to be incorporated on the right side of the vehicle just aft of the front wheels. Actuating this switch will cut all electrical power to the vehicle, stopping the prime mover, computer, and all other equipment. In this instance, the e-brake pneumatic solenoid would open, (normally held closed by battery power) setting the e-brake in the "applied" position.

D. E-Stops

1. The main program will poll for an E-Stop once per cycle. In addition, the continuation of any cyclic or looped portion of the program would include a poll for E-Stop in a way that would make continuation of the program contingent on a clear E-Stop flag. Once an E-Stop signal *(pause)* is acknowledged the program will simultaneously output commands to center the steering, reduce throttle to idle, and apply hard braking. Once stopped the CPU would command the engine/transmission micro to select the neutral transmission gear, and it would continue to hold brake pressure until the E-Stop cleared. If for any reason the main program fails to execute the E-Stop properly, or fails to clear the E-Stop flag at any time during operation, *receives a "disable" command, or the external manual E-Stop switch is actuated*, the Compressed Gas Emergency Braking Device would open, actuating the brake master cylinder while breaking the ignition circuit to kill the engine. If this hard stop was software activated and the program was still running normally, it would wait and continuously poll for a Clear E-Stop. Once the E-Stop was cleared, the CPU would branch to the restart sequence if the engine had

stopped, would open the Compressed Gas Emergency Brake purge solenoid valve, and would resume operation from where it left off. We estimate that the E-Brake CO2 cylinder has the capacity to cycle the E-Brake cylinder at least ten times. All E-Stop functions will be tied to a "dead-man" time delay relay that will be reset by the CPU each time the E-Stop flag clears. If at any time for any reason the software fails to clear the E-Stop flag, the time delay relay will activate within a few seconds, automatically firing the E-Brake Cylinder and breaking the engine ignition circuit.

2. The manual E-Stop switch would be a NEMA style normally closed latched single pushbutton station mounted to the exterior of the vehicle in as accessible a location as is practical. Activation of the manual E-Stop switch would break the same circuit monitored by the time delay relay, actuating the E-Brake cylinder and breaking the engine ignition circuit. Once activated, the latter two E-Stop sequences would result in the brakes locking in the "applied" position, and the engine ignition circuit being broken. Movement of the vehicle after that is only possible by closing the E-Brake supply isolation valve and opening a manual bleeder valve to purge the E-Brake cylinder.

3. To ready the vehicle for towing, the brake would be released as described above. After that, the four-wheel-drive style hubs at the input side of the rear axle gear reduction drives would be placed in the "free" position, disconnecting the rest of the driveline from the rear wheels. The vehicle would then have to be rolled backwards for about ten feet or so to completely disengage the hubs. The front end of the vehicle would have to be suspended for towing, as the gearmotor driven steering mechanism will not allow for the wheels to naturally track while being towed. If the steering gearmotor is uncoupled for towing, the front wheels can be left on the ground. We will attempt to incorporate manual overrides for most vehicle functions where it is practical, such as a means to disconnect and manually operate the transmission gear selector to engage the parking pawls, or a way to readily disconnect the steering gearmotor. If a "parking brake" function is needed, the E-Brake purge may be closed and the E-Brake supply re-opened. The E-Brake solenoid valve will be plumbed in a normally open position (brake applied) and will only close when commanded to by the CPU.

E. Radiators

1. The lasers are class IIIa devices. The Polaroid Sonar Modules operate in a low-power ultrasonic range that is inaudible and ear safe. The rotating amber beacon is a halogen lamped DOT approved warning device. *The audible warning device is a 12-volt siren similar to what is found in car alarm systems. We do not have a means to accurately measure its decibel output, but suffice it to say one would not want to be near it without proper hearing protection.*
2. The only safety measure relating to the radiators is that the laser devices will only operate when commanded to by the CPU. Any E-Stop or accidental interruption of the program will terminate the function of the laser devices.

F. Environmental Impact

1. The large agricultural style tires mounted at a camber tend to scuff the ground a bit. Otherwise, the vehicle is light and relatively low powered.
2. The vehicle is roughly 96” tall by 96” wide by *about 212” long. We have not yet scaled the vehicle, but as it nears completion it appears that its weight will be closer to 2500 lbs than our original estimation of 2000 lbs.*
3. The vehicle has a *wheelbase of 133”* and a track width of 96”. Each tire running at low pressure should contact at least 150 square inches, giving a maximum (static) ground pressure of about 5.5 p.s.i. accounting for rearward weight bias.